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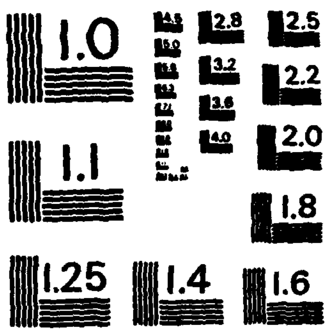

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Narrowband Electromagnetic Emissions from Jupiter's Magnetosphere

by

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U. of Iowa 82-26

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September 1982

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Submitted to Nature.

The research at The University of Iowa was supported by NASA through contract 954013 with the Jet Propulsion Laboratory and through grants NGL-16-001-002, NGL-16-001-043, and NAGW-337 with NASA Headquarters, and by the Office of Naval Research. The research at TRW was supported by NASA through contract 954012 with the Jet Propulsion Laboratory.

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER U. of Iowa-82-26	2. GOVT ACCESSION NO. AD-A121 646	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) NARROWBAND ELECTROMAGNETIC EMISSIONS FROM JUPITER'S MAGNETOSPHERE		5. TYPE OF REPORT & PERIOD COVERED Progress, September 1982
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. A. Gurnett, W. S. Kurth, and F. L. Scarf		8. CONTRACT OR GRANT NUMBER(s) N00014-76-C-0016
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Physics and Astronomy The University of Iowa Iowa City, IA 52242		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Electronics Program Office Office of Naval Research Arlington, VA 22217		12. REPORT DATE 30 September 1982
		13. NUMBER OF PAGES 22
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution is unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Submitted to Nature.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Narrowband Emissions Magnetosphere		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (see following page)		

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ABSTRACT

Recent studies of wideband plasma wave data from the Voyager 1 and 2 flybys of Jupiter have revealed the existence of narrowband radio emissions in the frequency range 1 - 12 kHz. These narrowband emissions are very similar to narrowband emissions previously discovered in the magnetospheres of Earth and Saturn, and are believed to be produced by mode conversion from electron cyclotron waves near the upper hybrid resonance frequency. This mode conversion process is apparently one of the basic mechanisms for generating planetary radio emissions.

INTRODUCTION

During the Voyager 1 and 2 flybys of Jupiter, the plasma wave instrument detected a series of narrowband electromagnetic emissions at frequencies between about 1 and 20 kHz. These emissions are remarkable both because of their extremely complex spectral structure, consisting of many closely spaced monochromatic emissions, and because similar types of narrowband emissions have been observed in the magnetospheres of Earth[1] and Saturn[2,3]. The frequency spacing of these emissions suggests that they are associated with electrostatic upper hybrid resonance waves that occur at odd half-integral harmonics of the electron cyclotron frequency. This type of electrostatic wave is known to be responsible for the narrowband emissions observed at Earth[1] via a mode conversion process. The mechanism for generating the narrowband electromagnetic emissions therefore appears to be a universal one, with possible applications to solar and other astrophysical radio sources. In this paper we describe the characteristics of the Jovian narrowband emissions and discuss possible mechanisms for generating these emissions.

OBSERVATIONS

An example of the Jovian narrowband electromagnetic emissions is illustrated in Figure 1 which shows a survey plot of the electric field intensities obtained from the 16-channel spectrum analyzer during the inbound Voyager 1 pass through the Jovian magnetosphere on March 3, 1979. The narrowband emissions show up on these plots as a relatively smooth feature in the 10.0-kHz channel from about 08 h to 10 h SCET (spacecraft event time) at a radial distance of about 42 R_J. The narrowband character of the radiation can only be discerned by the use of high resolution spectrograms from the wideband electric field waveform data, such as shown in Figure 2. These spectrograms, which consist of a sequence of 15-s intervals spaced a few minutes apart from about 9 h 40 min to 10 h 8 min, show that the radiation consists of a series of closely spaced narrowband emissions, each with a bandwidth of only a few hundred Hz, or less. These narrowband features are known to be electromagnetic emissions because they occur above the electron plasma frequency, f_p, in a frequency range where the only mode of propagation is the free space electromagnetic mode. The electron plasma frequency can be determined from the trapped continuum radiation, which is known to have a low frequency cutoff at the local electron plasma frequency[4]. The electron cyclotron frequency, f_c, which is the only other relevant frequency of the plasma is about 400 Hz in this region, well below the electron plasma frequency.

The sequence of spectrograms in Figure 2 shows that although the narrowband emissions do not change significantly during the 15-s duration of the spectrogram, marked changes occur during the several minute interval between spectrograms. Unfortunately, because gaps occur in the wideband data[5], it is not possible to follow the detailed temporal evolution of the spectrum. However, the spectrograms give the strong impression that the source consists of a large number of isolated lines between about 8 to 12 kHz, each of which is changing intensity on a time scale of a few minutes. The electric field strengths of the most intense bands range from about 10 to 30 μV/m. Occasionally, as in panel D at 7.4, 8.3 and 9.2 kHz, a series of lines can be identified that have a nearly constant frequency spacing, suggesting that the emission frequencies are harmonically related. In addition to the lines around 10 kHz another series of lines can be seen at lower frequencies superimposed on the trapped continuum radiation. These lower frequency emissions, which are evident in panel A at 2.7, 4.1 and 5.4 kHz, also have a harmonic frequency spacing. Similar narrowband features have been previously reported in the trapped continuum radiation at Jupiter[6]. The lines in trapped continuum radiation are usually not as narrow and sharply defined as the emissions observed above the continuum radiation.

At the present time, three events have been identified near Jupiter with characteristics of the type described above. The second of these events occurred during the outbound Voyager 1 pass through the magnetotail on March 6-7, 1979, at a radial distance of about 32 R_J. The spectrum analyzer data for this event are shown in Figure 3. The narrowband emissions in this case sweep downward in frequency, starting in the

17.8-kHz channel at about 22 h on March 6, and ending in the 5.62-kHz channel at about 3 h on March 7. A sequence of spectrograms illustrating the narrowband character of these emissions is shown in Figure 4. In this case the spectrograms have a 4-s duration and are separated by roughly half-hour intervals. Again the spectrum is characterized by many closely spaced lines with a tendency for harmonic frequency spacings. The downward drift in the average frequency of the lines with increasing time is clearly evident. The temporal variations of the individual lines is very complex. Some of the lines decrease in frequency with increasing time, whereas others remain at a fixed frequency with the intensity varying as the main emission band sweeps downward in frequency. The downward frequency drift continues until the lines merge into the trapped continuum radiation below about 5 kHz.

The third event was obtained during the Voyager 2 approach to Jupiter on July 4, 1979, at a radial distance of 71.5 R_J, very close to magnetopause. This case, shown in Figure 5, has very clear evidence of harmonic structure with a frequency spacing of about 200 Hz. Also, evident in the same region is a series of narrowband upper hybrid resonance (UHR) waves. From previous observations[6] these waves have been identified as an electrostatic mode at the upper hybrid resonance frequency, $f_{UHR} = (f_p^2 + f_c^2)^{1/2}$. The upper hybrid waves occur at discrete frequencies separated by the electron cyclotron frequency. Inspection of Figure 5 shows that the upper hybrid waves occur at the same frequency as the narrowband electromagnetic emissions, which strongly implies that the electromagnetic radiation is being generated by these electrostatic waves.

Because the Jovian decametric radiation[7] and kilometric radiation[8,9], are controlled by the rotation of Jupiter and tend to occur in a fixed longitude range, it is interesting to investigate the longitude at which the narrowband emissions occur. For the events on March 3 and March 6-7 the System III (1965) longitude of the spacecraft was 332° ± 36° and 4° ± 105°, respectively. For the event on July 4 the System III (1965) longitude was 314°. No longitude limits can be given for the third event because the duration cannot be accurately determined from the 16-channel survey data. These longitudes all fall in the same general region, centered on roughly 336°, suggesting that the rotation of Jupiter may have some control on the occurrence of these emissions. However, with only three events available for study, it is difficult to determine the strength of this rotational control.

DISCUSSION

These observations of Jovian narrowband electromagnetic emissions confirm the existence of the same type of radio emission process at three planets: Earth, Jupiter and Saturn. The similarity between the Jovian and Saturnian narrowband emissions is quite striking. At Saturn the wideband spectrograms show a series of narrowband emission lines[2,3] with characteristics essentially identical to those illustrated in Figures 2 and 4. At Earth wideband spectrum measurements with the ISEE 1 spacecraft show narrowband emission lines that are essentially identical to the narrowband emissions observed at Jupiter and Saturn (see Figure 7 of Kurth et al.[1]). The Jovian narrowband emissions may also be similar to a type of Jovian radio emission called narrowband kilometric radiation (nKOM) that has been previously reported by Kaiser and Desch[9]. The nKOM usually consisted of a single relatively narrowband emission near 100 kHz, somewhat above the frequency range (1 to 12 kHz) of the emissions described in this paper. It seems likely that if better frequency resolution were available it would be found that the nKOM actually consists of many closely spaced emission lines similar to those illustrated in Figures 2 and 4.

The best evidence of the origin of the narrowband electromagnetic emissions comes from terrestrial measurements, where a long series of observations indicates that the radiation is produced by electrostatic electron cyclotron waves near the upper hybrid resonance frequency[10,11,12]. The upper hybrid resonance instability occurs when the upper hybrid resonance frequency is near an odd half-integral harmonic of the electron cyclotron frequency, $f_{UHR} \simeq (n + 1/2)f_c$, where n is an integer[12,13,14,15]. The free energy for the instability is produced by a region of positive slope, $\partial f/\partial v_\perp > 0$, in the electron distribution function, such as occurs in a ring or loss-cone distribution. The instability is enhanced when a substantial number of cold electrons are present in the plasma.

The physical situation that is believed to be responsible for generating the narrowband emissions in the Jovian magnetosphere is illustrated in Figure 6, which shows a representative radial profile of the upper hybrid resonance frequency and the electron cyclotron frequency near the equatorial plane. Because the plasma is moderately dense near the equatorial plane the upper hybrid resonance is nearly the same as the electron plasma frequency, $f_{UHR} \simeq f_p$, and is therefore determined by the electron density profile. The dashed lines are the odd half-integral harmonics of the electron cyclotron frequency. The electrostatic waves occur at the points where the dashed lines cross the upper hybrid resonance frequency. Observations in the Earth's magnetosphere show that the electrostatic waves are converted directly to electromagnetic radiation with little or no frequency shift[1]. The mode conversion process could be either a linear escape mechanism associated with density gradients, of the type suggested by Oya[16] and Jones[11], or a nonlinear two-wave interaction, of the type discussed by Melrose[17].

Because of the quantized frequency spectrum of the upper hybrid waves, the escaping radio emissions consist of a series of lines with a quasi-harmonic frequency spacing, the exact frequencies of which are determined by the details of the electron density and magnetic field profiles. Because the electron density at Jupiter is often very irregular (note the variations of f_p in Figures 2 and 4), the emission frequencies are undoubtedly much more complicated than indicated by Figure 6, thereby accounting for the large number of lines and great complexity of the spectrum. Observations in the Earth's magnetosphere indicate that the source of the narrowband emissions is very patchy[1], consisting of numerous isolated regions, each emitting a frequency determined by the plasma parameters associated with that region.

As indicated in Figure 6 the narrowband emissions can in principal be generated either on the rising part of the electron density profile in the inner magnetosphere or in the region of rapidly decreasing density near the magnetopause. The line spacing of the emissions in Figure 5 (~ 200 Hz) is characteristic of the electron cyclotron frequency in the outer region of the magnetosphere, which suggests that these emissions are generated at or near the magnetopause. The radiation is then emitted inward, toward the planet, as illustrated in Figure 6. In other cases, such as in Figures 2 and 4, the emission frequency extends to frequencies so high, well above 10 kHz, that a magnetopause source is impossible. In these cases the radiation is emitted outward, from a source in the inner magnetosphere. If the emission frequency is below the magnetopause plasma frequency, then the radiation is permanently trapped inside the low density magnetospheric cavity. This radiation can then account for the trapped continuum radiation, as has been previously suggested by several authors[18,19]. The broadened width of the lines detected in the trapped continuum radiation (see panel A of Figure 2) is believed to be due to fluctuations in the position of the magnetopause, which cause Doppler broadening as suggested by Barbosa[19]. If the emission frequency is above the magnetopause plasma frequency, then the radiation can propagate freely away from the planet.

The downward frequency drift for the event shown in Figure 4 is strongly suggestive of a source moving outward away from the planet, emitting radiation near the local electron plasma frequency, similar to the mechanisms involved in type II and type III solar radio bursts. Based on the Jovian electron density profile given by Gurnett et al.[20], the narrowband emissions in Figure 4 are generated at radial distances of about 15 to 25 R_J, in the outer regions of the Io plasma torus. From the observed frequency drift rate the radial velocity of the source is estimated to be about 3 R_J/h or 60 km/s. It is unlikely that the source motion could be produced directly by the motion of a charged particle beam as in the case of solar radio bursts, because the energies, 0.01 eV for an electron and 18 eV for a proton, are too small to produce plasma instabilities in the hot Jovian plasma. More likely the source is associated with a cloud of plasma moving outward through the magnetosphere. Interchange instabilities caused by the centrifugal force in the rapidly rotating magnetosphere of Jupiter are expected to cause radial transport of plasma outward from the Io plasma torus, perhaps producing isolated clouds of plasma moving outward through the magnetosphere. Isolated events of the type observed could also be produced by temporal variations in the plasma source, possibly caused by changes in the volcanic activity of Io, which is the primary source of plasma in the Jovian magnetosphere. Because the upper hybrid resonance instability is sensitive to the cold to hot plasma density ratio[12,13,14,15,21], a cloud of relatively cool plasma from the Io torus would be expected to trigger the upper hybrid resonance instability as it moved through the hot outer regions of the magnetosphere.

Finally, we consider the possibility that the frequency drift could be caused by a frequency dependent latitudinal beaming of the radiation such as proposed by Jones[22] for the Jovian kilometric radiation. In this case the frequency shift would be caused by the changing magnetic latitude of the spacecraft as the planet rotates. This beaming mechanism predicts both upward and downward frequency drifts depending on the phase of the planetary rotation. At present, no events with an upward frequency drift have been observed. Furthermore, the latitude variation for the event in Figure 4 predicts a frequency drift opposite to what is observed. Thus, the latitudinal beaming model does not appear to provide a likely explanation for the observed frequency drift.

ACKNOWLEDGEMENTS

Work at The University of Iowa was supported by NASA contract 954013 with the Jet Propulsion Laboratory and grants NGL-16-001-002, NGL-16-001-043, and NAGW-337 with NASA Headquarters, and by the Office of Naval Research. Work at TRW was supported by NASA Contract 954012 with the Jet Propulsion Laboratory.

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FIGURE CAPTIONS

Figure 1 The electric field intensities from the 16-channel spectrum analyzer on Voyager 1 during the inbound pass through the Jovian magnetosphere. The narrowband electromagnetic emissions occur in the 10-kHz channel. The dashed line indicates the electron plasma frequency, $f_p = 9\sqrt{n_e}$ kHz, where n_e is the electron number density in cm^{-3}.

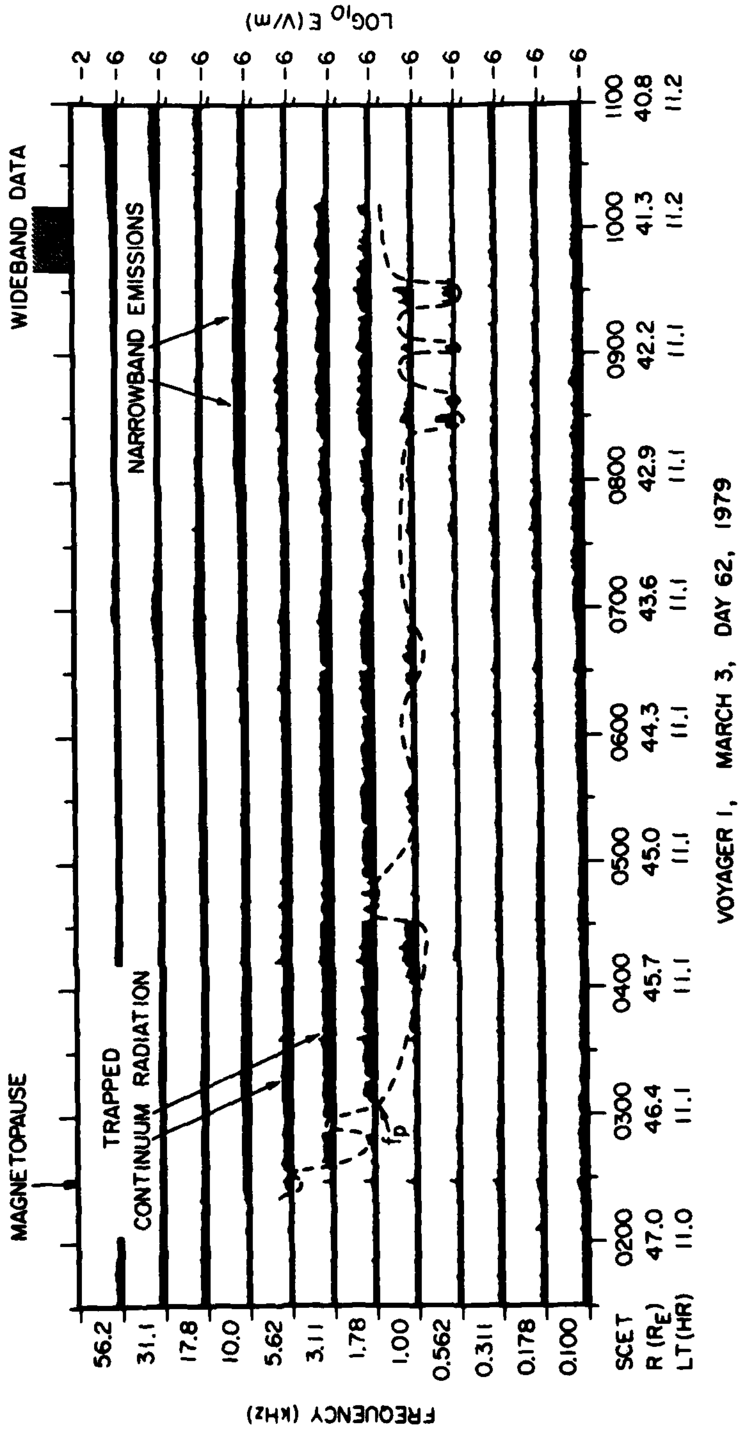
Figure 2 High resolution wideband spectrograms showing that the 10-kHz emission in Figure 1 consists of many closely-spaced narrowband emissions. The broadband emission just above the plasma frequency, f_p, is continuum radiation trapped in the low density magnetospheric cavity.

Figure 3 The 16-channel spectrum analyzer data from Voyager 1 during the outbound pass through the magnetotail. The narrowband emissions occur in the 17.8-, 10.0- and 5.62-kHz channels, sweeping downward in frequency with increasing time.

Figure 4 — A sequence of high resolution spectrograms for the event shown in Figure 3. Note the downward frequency drift with increasing time. This downward drift is suggestive of a source moving outward from Jupiter, emitting near the local electron plasma frequency as the source moves to increasing radial distance.

Figure 5 — A high resolution spectrogram of narrowband electromagnetic emissions detected near the magnetopause during the Voyager 2 encounter. The UHR waves are electrostatic emissions generated near the upper hybrid resonance frequency, f_{UHR}. These emissions occur at discrete frequencies separated by the electron cyclotron frequency, $f_c = 28B$ Hz, where B is the magnetic field in nT.

Figure 6 — A model illustrating a mechanism for generating the narrowband electromagnetic emissions in the Jovian magnetosphere. An electron cyclotron instability is believed to produce electrostatic waves at $(n + 1/2)f_c \approx f_{UHR}$. These waves are then converted to electromagnetic radiation by a mode coupling process.


C-G82-696-1
WIDEBAND DATA
MAGNETOPAUSE
TRAPPED CONTINUUM RADIATION
NARROWBAND EMISSIONS
f_p
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-2
-6
FREQUENCY (KHz)
56.2
31.1
17.8
10.0
5.62
3.11
1.78
1.00
0.562
0.311
0.178
0.100
SCET 0200 0300 0400 0500 0600 0700 0800 0900 1000 1100
R (R_E) 47.0 46.4 45.7 45.0 44.3 43.6 42.9 42.2 41.3 40.8
LT (HR) 11.0 11.1 11.1 11.1 11.1 11.1 11.1 11.1 11.2 11.2
VOYAGER 1, MARCH 3, DAY 62, 1979

Figure 1

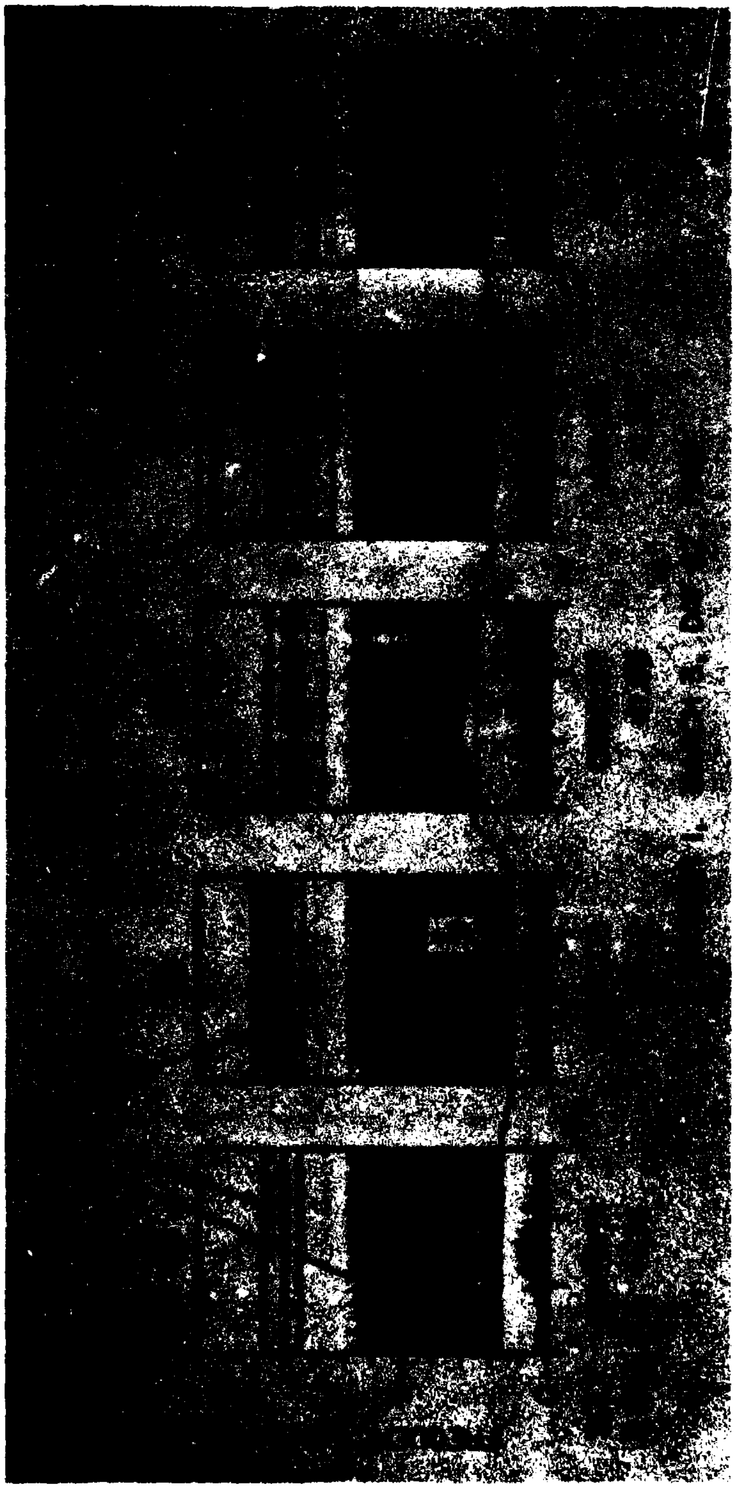
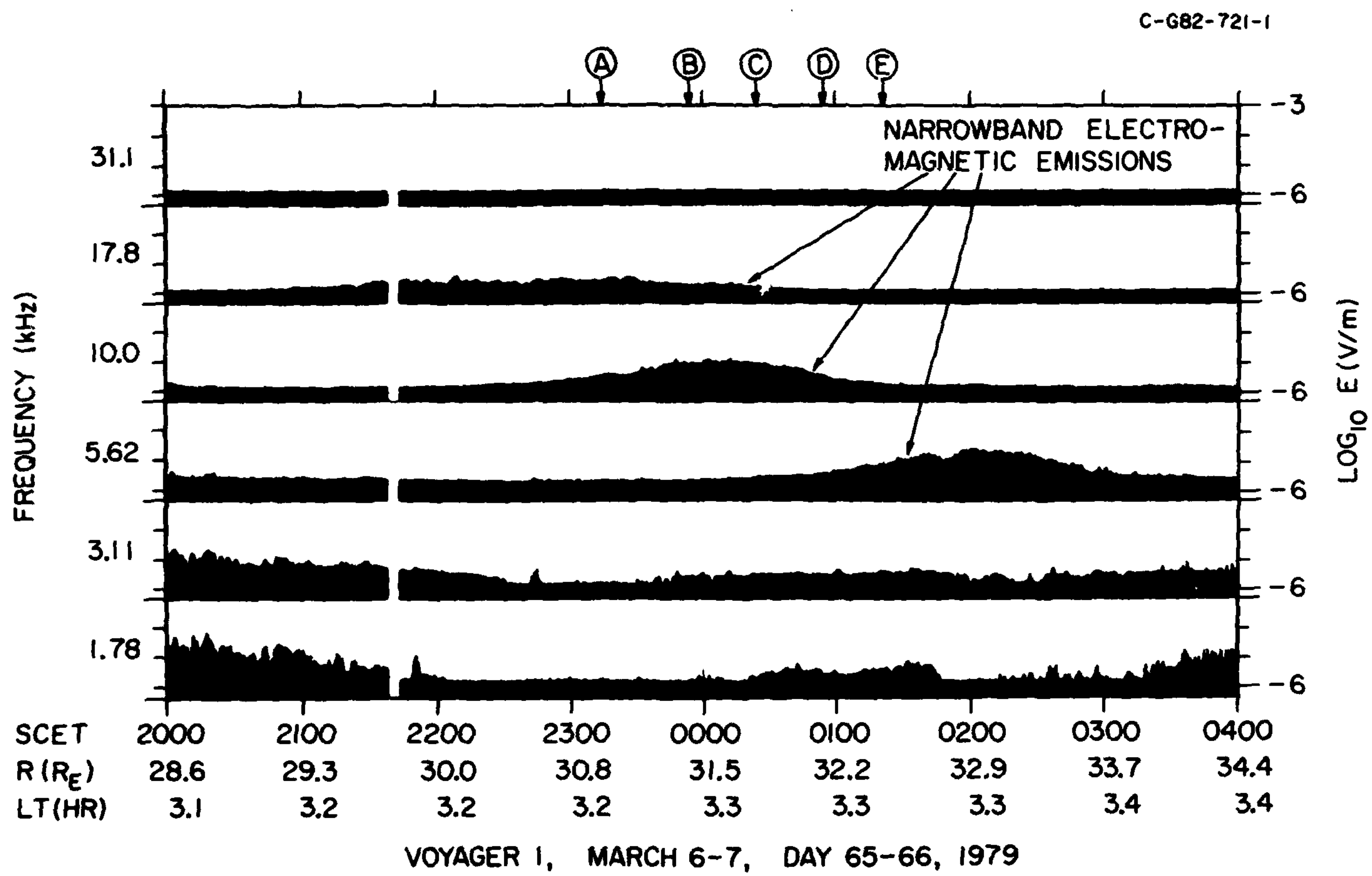


Figure 2


C-G82-721-1
A
B
C
D
E
NARROWBAND ELECTRO-MAGNETIC EMISSIONS
FREQUENCY (kHz)
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17.8
10.0
5.62
3.11
1.78
LOG10 E (V/m)
-3
-6
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R (RE) 28.6 29.3 30.0 30.8 31.5 32.2 32.9 33.7 34.4
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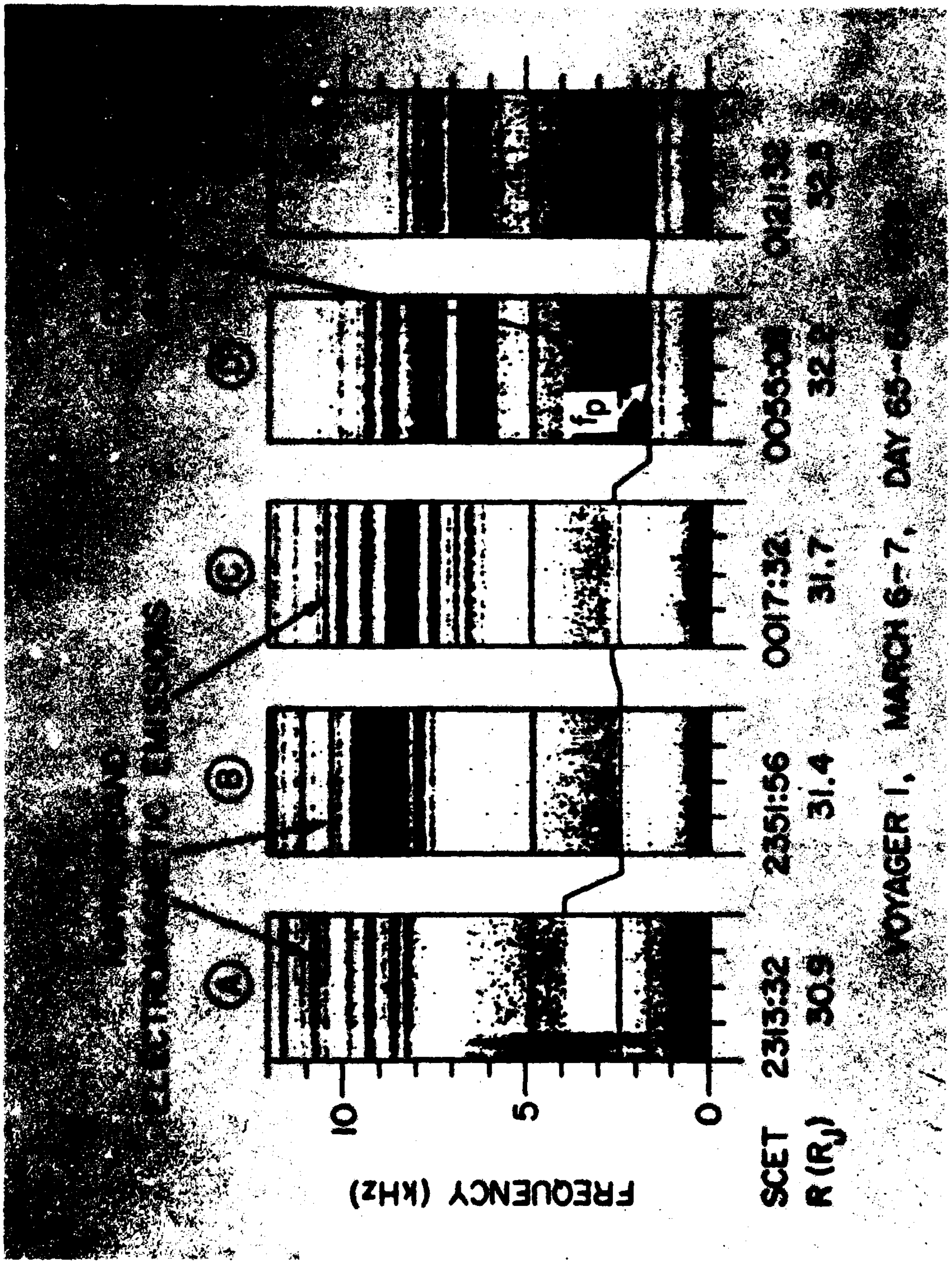
VOYAGER 1, MARCH 6-7, DAY 65-66, 1979

Figure 3



FREQUENCY (kHz)
10
5
0
SCET
R (R$_J$)
A
B
C
D
f_p
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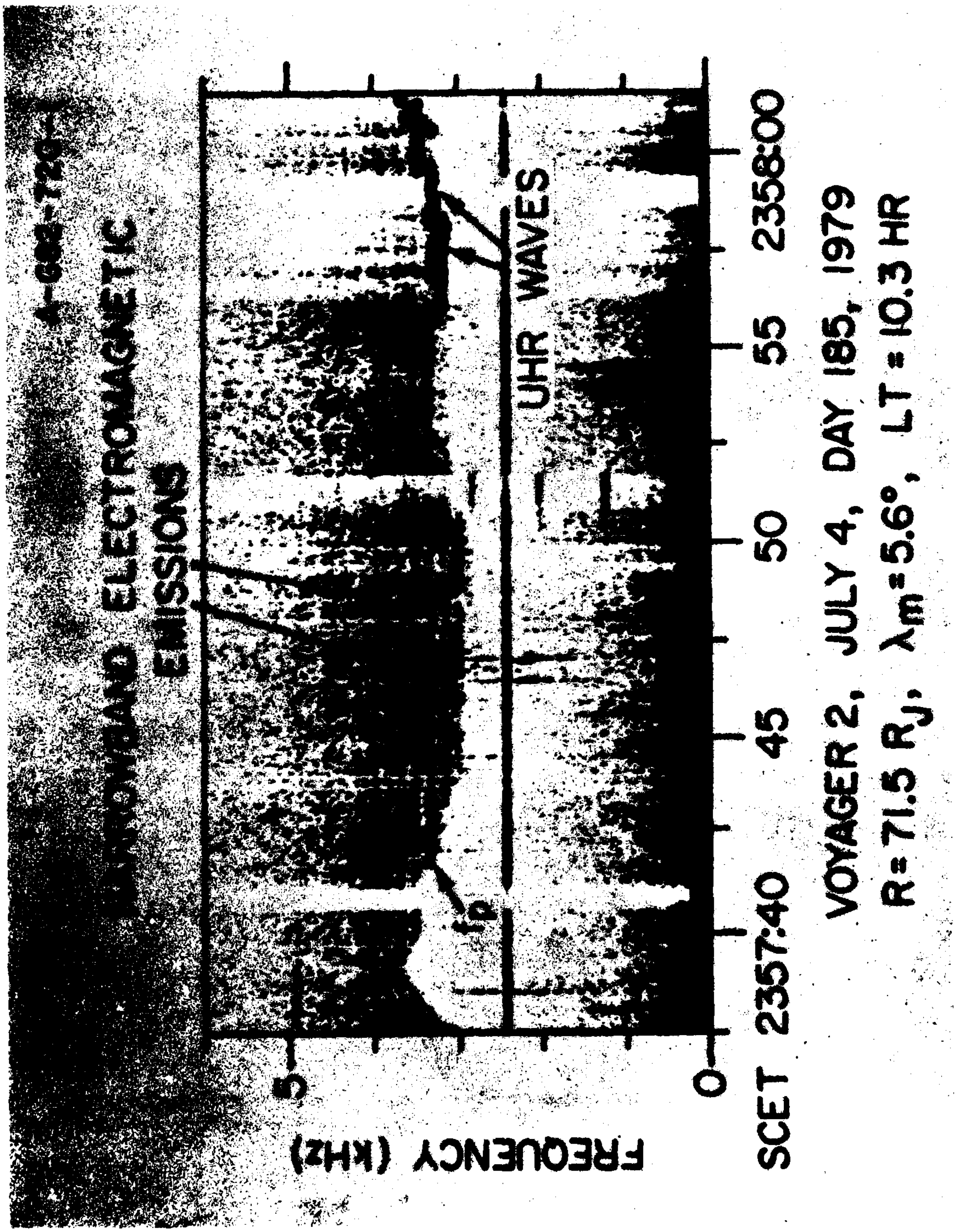
2351:56
0017:32
30.9
31.4
31.7
VOYAGER I, MARCH 6-7, DAY 65-

Figure 4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EMISSIONS
UHR WAVES
f_p
FREQUENCY (kHz)
5
0
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45
50
55
2358:00
VOYAGER 2, JULY 4, DAY 185, 1979
R = 71.5 R_J, λ_m = 5.6°, LT = 10.3 HR

Figure 5

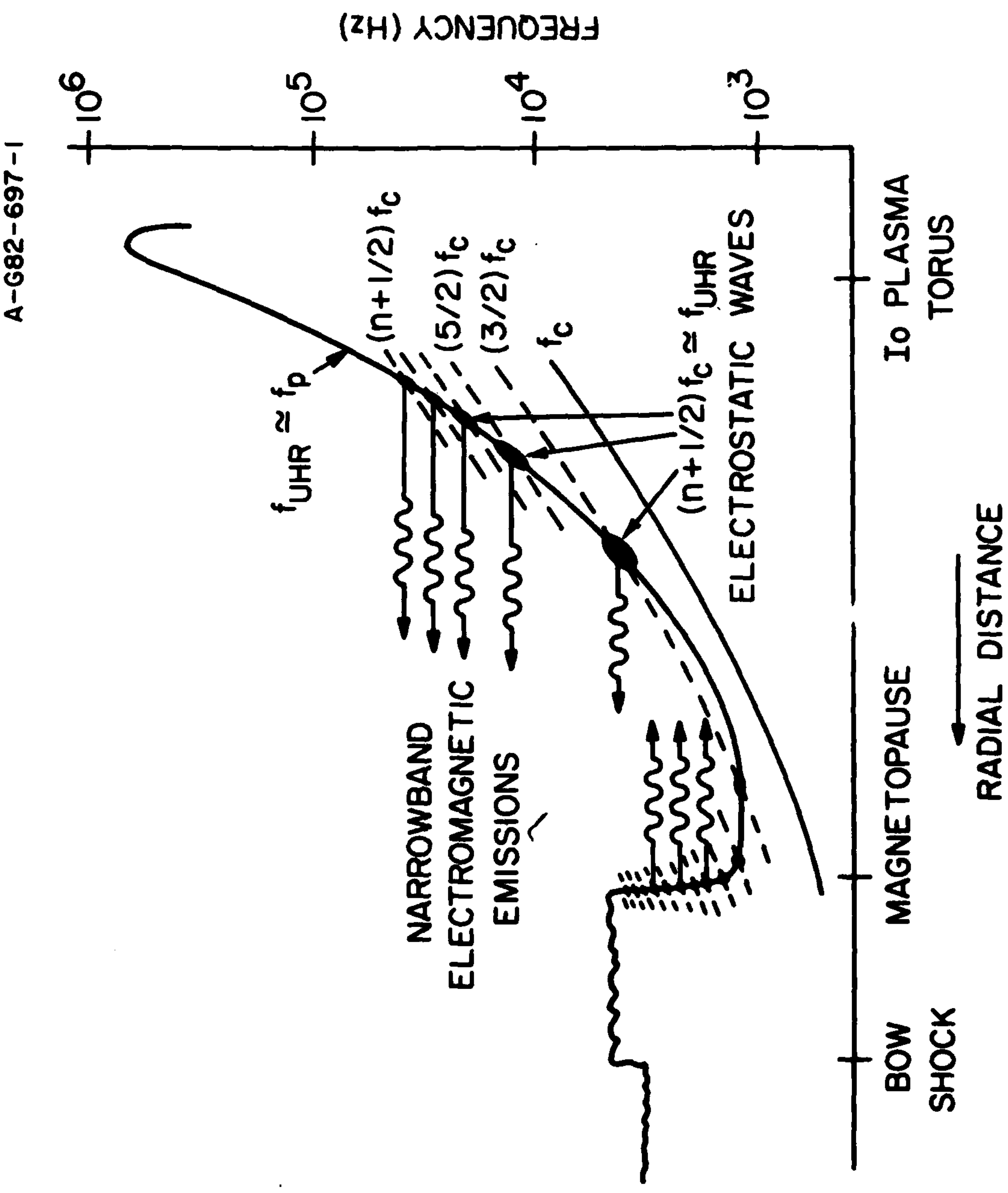
A-G82-697-1
FREQUENCY (Hz)
10^6
10^5
10^4
10^3
f_UHR ≃ f_p
(n+1/2) f_c
(5/2) f_c
(3/2) f_c
f_c
(n+1/2) f_c ≃ f_UHR
ELECTROSTATIC WAVES
NARROWBAND
ELECTROMAGNETIC
EMISSIONS
Io PLASMA
TORUS
MAGNETOPAUSE
BOW
SHOCK
RADIAL DISTANCE

Figure 6